

# A New Matrix/Fracture Multiscale Coupled Model for Flow in Shale-Gas Reservoirs

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## Summary

A new computational model for coupled gas flow in hydraulic fractures and multiporosity shale matrix is developed within the framework of multiscale modeling. The hydrodynamics in the network of hydraulic fractures are constructed by averaging the mass-conservation equation across the fracture aperture, giving rise to an averaged balance law supplemented by a source term arising from the jump in the gas flux from the shale matrix. The resultant flow equation in the fracture is coupled with a new pressure equation that governs the averaged gas movement in the shale matrix. Such a pressure equation exhibits a new storage coefficient and is rigorously derived by homogenizing the pore-scale model of gas flow in the interparticle pores, partially saturated with water, lying adjacent to the nanopores within the kerogen and impermeable inorganic matter composed of a reactive clay and an inert solid. The free gas at the interparticle pores is assumed at local thermodynamic equilibrium with the dissolved gas in the water and adsorbed gas lying in the nanopores of the kerogen aggregates and at the surface of the active clay. The constitutive laws for the partition coefficients, which appear in the pressure equation, are derived from the adsorption isotherms, which are rigorously constructed from the thermodynamics of confined gases on the basis of the density-functional-theory (DFT) approach. Numerical simulations of both canonical and real computational examples of gas primary recovery in the Barnett, Marcellus, and Eagle Ford formations illustrate the potential of the multiscale approach proposed herein in computing production in different flow regimes.

## Introduction

Shale-gas unconventional reservoirs are characterized by a very-fine-grain texture with ultralow permeability (nanodarcy scale) (Sakhaee-Pour and Bryant 2012) and consequently release trapped gas very slowly, leading to the development of expensive and sometimes unfeasible procedures. The economic viability of such formations hinges on effective stimulation by creating very-complex hydraulic-fracture networks that connect a huge reservoir surface area to the wellbore.

The complexity underlying the multiscale description of such a geological formation lies in the presence of multiple substructures arising from multimodal pore-size distributions (Sondergeld et al. 2010), the presence of natural and hydraulic fractures, along with a wide diversity of solid phases, such as inorganic matter (clay, calcite particles, quartz, feldspar) and organic material (kerogen). In addition to fractures, distinct levels of pores appear associated with the gas-wet kerogen and water-wet system of nanometer to micrometer interparticle pores, which provide the pathways for gas movement. In such a complex microstructure, kerogen appears as random scattered inclusions in the inorganic phase (Yan et al. 2013), with the percentage quantified by the total organic carbon (TOC) (Akkutlu and Fathi 2012). In addition to organic matter, which acts as storage sites for adsorbed gas in the intrakerogen nanopores, the clay fraction (illite and kaolinite) of

the inorganic matter also acts as potential surface-adsorption sites for methane ( $\text{CH}_4$ ) (Ji et al. 2012; Liu et al. 2013; Jin and Firoozabadi 2013). Thus, in addition to the coupling between hydraulic fractures and shale matrix flows, very-complex adsorption phenomena occur in both organic and inorganic matter along with the partition mechanism between free and dissolved gas in the interparticle pores partially saturated by water.

The multiscale portrait of the medium is characterized by four natural length scales (Fig. 1). The first is the nanoscale, the local description of which aims at capturing the anomalous behavior of the gas in the intrakerogen nanopores. The second is the microscale, where the kerogen aggregates are envisioned as a homogenized solid phase composed of kerogen particles and sorbed gas distinct from the interparticle pores and inorganic-matter systems. Next is the mesoscale, where a three-phase system is homogenized, forming the shale matrix consisting of a distinct phase of the hydraulic fractures. Finally, at the macroscale, the  $n$ -dimensional hydraulic fractures are replaced by  $(n-1)$ -dimensional objects immersed in the reservoir with local hydrodynamic properties replaced by their averaged values across the fracture aperture (Frih et al. 2008).

Reactive transport takes place at distinct spatial and temporal scales (Clarkson et al. 2012). In particular, we may highlight gas dissolution in the water phase in the interparticle pores; adsorption of gas within kerogen aggregates and on the clay surface; Darcy flow of free gas with higher apparent permeability induced by Knudsen effects at the pore wall (Mason and Malinauskas 1983; Sakhaee-Pour and Bryant 2012); classical Fickian diffusion of the dissolved gas in the water phase; and Darcy/Forchheimer-type flows (Forchheimer 1901) in the highly permeable fracture system.

The behavior of the sorbed gas is usually described by the classical Langmuir isotherm, for which the accuracy is restricted to the monolayer adsorption picture (Yu and Sepehrnoori 2014), where the characteristic length of the nanopores  $l$  is higher than the diameter of the  $\text{CH}_4$  molecule  $d$ . In the case of ultra nanopores where  $l < 5d$ , more-sophisticated theories have to be applied to construct isotherms and compute partition coefficients. To this end, we proceed within the framework of the DFT, where the grand canonical potential of the inhomogeneous gas is represented in terms of a functional relation of the local-density profile (Rosenfeld 1989; Kierlik and Rosinberg 1991). Minimization of this potential under a constant chemical-potential constraint, together with proper representations of the excess free energy and exterior potential, provide the local-density profiles (Rosenfeld 1989; Kierlik and Rosinberg 1991). For the representation of the functional dependency of the free energy on the local-density profile, we adopt a perturbative approach commonly referred to as the fundamental measure theory (FMT), where the excess free energy is decomposed into a hard sphere as van der Waals components (Rosenfeld 1989).

We establish the precise bridging between the anomalous behavior of the gas in the nanopores and the flow in the interparticle pores to establish our microscopic model. This local description is scaled up to the homogenized mesoscale associated with the shale matrix and further coupled with the mean flow in the hydraulic fractures, giving rise to the macroscopic picture of gas movement. The multiscale model captures the local physics of organic and inorganic matter coupled with flow of free gas and